Fisheries and Oceans Canada | Pêches et Océans Canada
Science | Sciences

Canadian Science Advisory Secretariat (CSAS)

Research Document 2013/011

Central and Arctic Region

Updated stock-dynamic model for the Northern Hudson Bay narwhal population based on 1982-2011 aerial surveys

Michael C.S. Kingsley[1], Natalie C. Asselin[2] and Steven H. Ferguson[3]

[1] Rua Principal 191, Cortiça, P.O. Box 3, 3300–357 São Martinho da Cortiça, Portugal

[2] PO Box 1116, Churchill, Manitoba R0B 0E0

[3] Fisheries and Oceans Canada, 501 University Crescent, Winnipeg, Manitoba R3T 2N6

April 2013

Canada

Foreword

This series documents the scientific basis for the evaluation of aquatic resources and ecosystems in Canada. As such, it addresses the issues of the day in the time frames required and the documents it contains are not intended as definitive statements on the subjects addressed but rather as progress reports on ongoing investigations.

Research documents are produced in the official language in which they are provided to the Secretariat.

Published by:

Fisheries and Oceans Canada
Canadian Science Advisory Secretariat
200 Kent Street
Ottawa ON K1A 0E6

http://www.dfo-mpo.gc.ca/csas-sccs/
csas-sccs@dfo-mpo.gc.ca

© Her Majesty the Queen in Right of Canada, 2013
ISSN 1919-5044

Correct citation for this publication:

Kingsley, M.C.S., Asselin, N.C., and Ferguson, S.H. 2013. Updated stock-dynamic model for the Northern Hudson Bay narwhal population based on 1982-2011 aerial surveys. DFO Can. Sci. Advis. Sec. Res. Doc. 2013/011. v + 19 p.

TABLE OF CONTENTS

ABSTRACT iv

RÉSUMÉ v

INTRODUCTION 1

METHODS 1
- SURVEY METHODS 1
- STOCK-DYNAMIC MODELLING METHODS 2
- DATA 3

RESULTS 4
- VISIBILITIES OF EARLY SURVEYS 4
- MODEL PERFORMANCE 5
- STOCK DYNAMICS, INCLUDING 2011 SURVEYS 5

DISCUSSION 7

CONCLUSION 10

REFERENCES 11

APPENDIX 1. MATHEMATICAL DESCRIPTION OF THE MODEL 12

APPENDIX 2. DATA NEAR-SURFACE TIME 13

APPENDIX 3. DATA ON LANDED CATCHES 14

APPENDIX 4. *BUGS* CODE FOR STOCK-DYNAMIC MODELLING OF NORTHERN HUDSON BAY NARWHALS 16

ABSTRACT

The Northern Hudson Bay narwhal population has been assessed from aerial surveys flown in the early 1980s, 2000, 2008, and 2011. The August 2011 survey provided information necessary for a full assessment of the population. A stock dynamic model using Bayesian methods and run on the OpenBUGS platform was developed in 2010 based on surveys up to 2008. Here, we update this model with the 2011 survey results, using adjustments for different survey methods (Asselin and Ferguson 2013) to assess the population size indices, and with the catch history to inform management of this population. To minimize differences due to the changes in survey methods, the 2011 data were re-analysed as though it had been collected and recorded using the recording methods of 2000. The valid information on stock dynamics comes from the differences between the 1982–84 surveys and those flown in 2000 and 2011. The dynamics of the population was modelled as a constant growth rate and limits to population growth at high numbers were not considered. In the present document, catch was the only mortality taken into account, and loss rates were considered to have the same distribution over the whole period. Three survey treatment options were run:

(1) 2011 surveys not used in trend analysis;

(2) original 2011 line-transect survey analysis used; and

(3) re-analysis of 2011 according to 2000 survey methods (i.e., multi-strip survey) used.

The serial correlation of process errors is higher for the line-transect analysis of the 2011 observations, indicating that the results obtained by analysing the observations as a multi-strip survey (option 3) fit better with the earlier surveys, the catch sequence, and the assumption of a constant population growth rate. Under option 3, the population has annual growth of 1.2% and can barely support landed catches of 75 a year. The population trajectory has been more or less flat since the late 1990s with mean landed catches since then of about 84 a year; the odds of any decrease in numbers are estimated at 48% over 10 years. The estimated probability that the population will decline increases with time, even for catch levels that are associated with a slightly increasing population, because of the rising uncertainty of projections into the future. The results from this modelling exercise are uncertain and do not provide reliable estimates of future sustainable catches and further surveys are required. We conclude that management should continue to use Potential Biological Removal (PBR), rather than the risk-based approach reported in this document, until more surveys are undertaken.

Mise à jour du modèle de dynamique de stock pour la population de narvals du nord de la baie d'Hudson selon les relevés aériens de 1982 à 2011

RÉSUMÉ

La population de narvals du nord de la baie d'Hudson a été évaluée au moyen de relevés aériens effectués au début des années 1980 et en 2000, 2008 et 2011. Le relevé mené en août 2011 a permis d'obtenir les données nécessaires à la réalisation d'une évaluation complète de la population. Un modèle de dynamique de stock faisant appel aux méthodes bayésiennes et fonctionnant sur la plateforme OpenBUGS a été élaboré en 2010 à partir des relevés effectués jusqu'en 2008. Nous présentons ici une mise à jour de ce modèle fondée sur les résultats du relevé réalisé en 2011. Pour évaluer les indices de la taille de la population, nous avons dû nous ajuster aux différentes techniques de relevé (Asselin et Ferguson 2013). La mise à jour est également basée sur l'historique des prises, afin de guider la gestion de cette population. Pour réduire les écarts attribuables aux changements de techniques de relevé, les données de 2011 ont été analysées à nouveau comme si elles avaient été recueillies et consignées selon les méthodes utilisées en 2000. Les données valides sur la dynamique des stocks résultent des différences entre les relevés de 1982 à 1984 et ceux de 2000 et 2011. La dynamique de la population a été modélisée sous forme de taux de croissance constant, et les facteurs limitant la croissance de la population n'ont pas été pris en compte pour ce qui est des nombres élevés. Dans le présent document, les captures constituent la seule cause de mortalité prise en considération. On a considéré que les taux de perte sont les mêmes pour toute la période. Trois options ont été appliquées dans le dépouillement des relevés :

(1) exclusion des relevés de 2011 dans l'analyse des tendances;

(2) utilisation de l'analyse originale des relevés de 2011 réalisés grâce à la technique de transects en ligne;

(3) utilisation de la nouvelle analyse des relevés de 2011 suivant les techniques de relevés de 2000 (c.-à-d., relevé par échantillonnage en bandes).

La corrélation sériale des erreurs de dépouillement est plus élevée dans l'analyse des observations de 2011 faisant appel à la technique de transects en ligne. Cela indique que les résultats issus de l'analyse des observations menée sous forme de relevé par échantillonnage en bandes (option 3) concordent davantage avec les résultats des relevés antérieurs, la séquence des prises et l'hypothèse d'un taux de croissance constant de la population. Avec l'option 3, la population connaît une croissance annuelle de 1,2 % et peut à peine supporter un débarquement annuel de 75 prises. La trajectoire de la population est plus ou moins stable depuis la fin des années 1990. La moyenne des prises débarquées est depuis d'environ 84 individus par année; la probabilité que ces chiffres diminuent au cours des dix prochaines années est estimée à 48 %. La probabilité estimative que la population connaisse un déclin augmente avec le temps, même pour les niveaux de prises associés à une population en légère croissance, en raison de l'incertitude des prévisions qui augmente avec le temps. Les résultats de cet exercice de modélisation sont incertains et ne fournissent pas pour l'avenir d'estimations fiables des niveaux de captures durables. Par conséquent, d'autres relevés devront être effectués. Nous sommes parvenus à la conclusion que la direction devrait continuer à utiliser la méthode du prélèvement biologique potentiel (PBP) plutôt que l'approche axée sur les risques présentée dans ce document, jusqu'à ce que d'autres relevés soient menés.

INTRODUCTION

A stock-dynamic model of the population of narwhals in Northern Hudson Bay was built and run. Among the objectives were: to review the sustainability of hunting at the levels of recent years, which appear to have been on average significantly larger than before about 1999; to include the most recent survey, flown in 2011 over a larger study area than its predecessors; to re-evaluate the 2008 survey, which returned a low estimate of population size but was plagued with problems of weather and sea-ice; and to estimate a sustainable take from the population.

Surveys of this population have been carried out since the early 1980s and the methods used have evolved. In common with the evolution of survey methods elsewhere, the tendency has been to import more and more corrections to visual surveys for animals not seen by the observers. Inclusion of survey results in stock-dynamic models therefore requires an evaluation of whether results of surveys that used different methods are comparable with one another and can be used to estimate trend in numbers (Asselin and Ferguson 2013).

In particular, a survey flown in 2011 (Asselin et al. 2012) imported a significant suite of features not found in the previous visual surveys flown in 2000. They included the use of two observers on each side of the aircraft, a photographic record that could be used to check some of the doubtful sightings, clinometer measurement of sighting angle, and line-transect analysis, which bases the estimate of numbers on the density of animals recorded in the strip near the transect line in which it is highest. The 2011 survey produced higher estimates of numbers than previous surveys in areas common to both, leading also to higher estimates of population growth rate and, therefore, of sustainable future catch. In an attempt to elucidate possible causes of the higher estimates, the observations made in 2011 were re-analysed as though they had been recorded using the methods applied in 2000.

This document presents the results of including these re-analysed results in the population model and, to the degree possible, draws conclusions on the comparisons available.

METHODS

SURVEY METHODS

Essentially, three methods have been used for making and recording observations in aerial surveys of the narwhal population in northern Hudson Bay. One was a photographic strip-transect method, used in 1982, 1983, 1984 (Richard 1991), 2000 (Bourassa 2003) and 2008 (Richard 2010). A second method, used for two surveys in 2000, was a multi-strip visual survey, in which observations, made by one observer on each side of the aircraft, were binned into 200-m-wide strips using window marks and then analysed using line-transect methods (Bourassa 2003) with the 'DISTANCE' package (Thomas et al. 2010). A visual strip-transect survey flown in 1982 has hitherto been considered indistinguishable from the multi-strip surveys of 2000; this assumption is examined in the present document. The third method, used in 2011, was a line-transect visual survey in which sighting angles were recorded using clinometers to be later converted to distances and then analysed by line-transect methods, two observers on each side of the aircraft allowed a correction for missed targets, and a simultaneous photographic record allowed checking of doubtful sightings (Asselin et al. 2012).

In a later re-analysis of the 2011 observations the calculated sighting distances were binned into 200-m-wide strips as in 2000, and only observations by primary observers were used. The resulting data set was then analysed using line-transect methods with the 'DISTANCE' package as in 2000.

The survey flown in 2011 included, on the recommendation of local people, a considerable extension of the survey area southwards in Roes Welcome Sound and into Wager Bay. These areas had not been covered by any previous survey. They turned out to hold a considerable number of narwhals, which are presumably part of the stock supporting the recorded harvests. They are therefore relevant to assessing the sustainability of the hunt and estimating the population rate of increase needed to sustain it; they are also useful in comparing the different analyses of the 2011 data. They were included in the analysed datasets as separate surveys.

Survey data and information on survey coverage was taken from Bourassa (2003), updated with information on the 2008 photographic survey from Richard (2010) and on the 2011 survey from Asselin et al. (2012). Earlier documents were referred to for technical information on the photographic methods used in the early 1980s and in 2000. The surveys essentially compose few data points. The series flown in 1982–84 have such similar results and span so short an interval that they give little information on stock dynamics, only on precision and relative visibility of different types of survey. Similarly, the differences between the three results from 2000 yield information on precision and visibility, but not on dynamics. The 2008 survey had problems with weather, ice cover, and equipment, was considered at the time to be unreliable, and has not been used in the present analyses. The valid information on stock dynamics comes from the differences between the 1982–84 surveys and those flown in 2000 and 2011.

STOCK-DYNAMIC MODELLING METHODS

A model was built to be fitted to the available data by Bayesian methods and coded for the OpenBUGS platform. It is similar to the model developed and run to review sustainability of hunting of the northern Hudson Bay narwhal population based on the 1982–2008 aerial surveys (Kingsley et al. 2012). The model is described in detail in Appendix 1. Briefly, it comprised five components that were more or less independent.

The visibility of narwhals to photographic survey was estimated from data on the proportion of time spent within 2 m of the surface as recorded for narwhals tagged with satellite-linked data tags (Westdal 2008).

Reported landed catches were converted to an uncertain true catch by correcting for lost animals.

Survey estimates of surface-visible numbers were corrected for the varying coverage of the different surveys, which did not all cover the same study area. A binary data file was constructed from survey-coverage maps to define which divisions of the overall study area had been included in each survey, and the model was coded to estimate the distribution of the population from this information and the survey results.

Surface-visible numbers were corrected to total numbers by applying visibility corrections. Standard visibility corrections for photographic and visual surveys were supplemented by *ad hoc* survey-specific correction factors that could be used to prevent selected surveys from influencing calculations of population trend but allow them to influence estimates of population distribution between divisions of the study area.

Neither the range, the quantity, nor the quality of the data would permit fitting any kind of density-dependent growth rate, so total numbers were progressed from year to year by applying a constant growth rate and deducting the true catch. Modelled total numbers were fitted to survey estimates.

Prior distributions were in general cast as uninformative, except for process error. Narwhals have a gross annual birth-rate somewhere near 10% and are long-lived, so it was appropriate to model the process error as small, in default of making the stock dynamics completely deterministic. The prior distribution for loss rate was also informative.

The model fitted population growth, minus catches, and visual-survey visibility in an effort to get all the surveys close to the population trajectory. At the same time, it juggled the estimates of population proportions in five divisions of the survey area (i.e., Repulse Bay and Frozen Strait, Gore Bay and Lyon Inlet, north-west Foxe Channel, north-eastern Roes Welcome Sound, and main Roes Welcome Sound with Wager Bay) with information on the coverage of the different surveys so that the resulting estimate of total population would lie on the modelled population trajectory.

The same model was also coded as an Excel spreadsheet model for solution using Excel Solver, to make some comparisons for which the deviance statistics output by OpenBUGS appeared to be misleading. In particular, the spreadsheet model was used to investigate whether the visual surveys of 1982 and 2000 should necessarily be considered to have different visibility from the photographic surveys.

DATA

Data on near-surface time comprised mean values obtained from nine narwhals tagged in northern Hudson Bay (Westdal 2008). The unweighted mean of nine means was 32% with a Standard Deviation (SD) of 5% (Appendix 2).

The model incorporated reported landed catches for 1977–2011. Going further back the number of missing reports increases and as there were no surveys before 1982 using earlier data would provide no information on stock dynamics. The mean level of reported catches was 19 in 1977–97, but 84 in 1998–2011 (Appendix 3). In both periods the coefficient of variation (CV) of the reported catch was 45–55% but in neither was there a strong increasing or decreasing trend.

There is little accurate information on loss rates in the hunt. Narwhals in northern Hudson Bay are not hunted from a floe edge—where losses tend to be largest—but near shore in open water, and Richard (2008) estimates losses from this population to be relatively modest (28% average ratio of lost : landed).

A data file for survey coverage was constructed from maps provided in the various survey reports. Most surveys did not tabulate results for different divisions of their survey areas. The prior distribution for the proportions of the population found in the divisions of the study area was based on areas tabulated in the report of the 2011 survey.

RESULTS

VISIBILITIES OF EARLY SURVEYS

It was necessary to assume that the three photographic surveys flown in the early 1980s all had the same visibility as the one flown in 2000. All were flown at 3000 feet with a 6-inch lens, and while there were differences in frame size and film type, the available documentation does not comment on how these differences might have affected the interpretation of the imagery.

Testing the assumption that the strip-transect visual survey of 1982 had the same visibility as the two flown in 2000 was equivalent to comparing two estimates of population growth rate, one based on the four photographic surveys and one based on the three visual surveys. The visual-survey results from 2000 have so much scatter that a precise test is not possible. The data appeared to show that the visibility in the strip-transect survey of 1982 was a little less than that in the multi-strip surveys of 2000. The visibility differences between the visual surveys and the photographic surveys were also small. Likelihoods from the spreadsheet model for four different assumptions about visibility are tabulated (Table 1).

Table 1. Maximum-likelihood estimates from spreadsheet modelling of northern Hudson Bay narwhal population dynamics from surveys in 1982–2000.

Assumption on visibilities	Log likelihood	Relative information[1]	Estimate of annual growth (%)	Visibilities (strip : multi-strip : photo)
1. All types are different	28.47	26.47	1.65	72 : 91 : 100
2. 1982 strip-transect same as 2000 multi-strip	28.01	27.01	1.78	84 : 84 : 100
3. 2000 multi-strip same as photographic	28.27	27.27	1.55	72 : 100 : 100
4. All (visual and photographic) the same	27.06	27.06	1.67	100 : 100 : 100

[1] without small-sample-size correction

The effects of these assumptions on the fitting process were as follows.

Assumption 1. The visual surveys having different or unknown visibilities had no influence on the population trend line, which was fitted to the photographic surveys. The visibilities of the visual surveys were calculated according to where their results lay relative to the trend line.

Assumption 2. The slope of the population trend line was fitted to the results of the photographic surveys and to the difference between the visual surveys of 1982 and 2000. The slope was greater than under assumption 1 owing to the greater difference between the visual surveys than between the photographic surveys. An ordinate was fitted to the photographic surveys, and the visibility for the visual surveys was calculated from where their results lay relative to that line.

Assumption 3. The trend line was fitted to the photographic surveys and the 2000 multi-strip surveys. The visibility of the 1982 visual survey was calculated from its position.

Assumption 4. The trend line was fitted to all survey results as reported.

The likelihood and information statistics resulting from these assumptions hardly differed. It appeared best to conclude that the visibility of all these early surveys was the same. This conclusion made effective use of all the data and led to an intermediate estimate of the population growth rate. The data did not lead convincingly to any other conclusion. The assumption that the visual surveys *necessarily* had different visibility from the photographic had little support (Table 1).

We therefore proceeded to investigate the implications of the surveys flown in 2011 and the re-analysis of the observations from those surveys, assuming equal visibilities for all surveys in 1982–2000 and using the Bayesian fitting process and the model described in earlier documents and in Appendix 4. Three treatments were modelled: with the 2011 surveys made ineffective by fitting free correction factors; with the 2011 original line-transect analysis included in the surveys used (correction factor fitted to the results of the re-analysis of the 2011 data); and with the re-analysis of the 2011 data according to the methods of the 2000 survey made effective and the original line-transect analysis correction-factored out of the calculation of population trend.

MODEL PERFORMANCE

The model (Appendix 4) was easily compiled, initialised and run using the OpenBUGS platform. The small amount of data led to skewed posterior distributions for some variables, so some of the deviance statistics output by OpenBUGS were not reliable.

The model fitted more parameters than there were observations, so many correlations between parameter estimates were significant and some were high. However, in spite of the many parameters to be fitted to so little data, most of the prior distributions were markedly updated by the Bayesian fit. There were two principal exceptions. One was the loss correction to reported catches. The data contains no information on loss rates, so the posterior distribution of this parameter was the unchanged prior. However, it had only one significant correlation, of about +8% with the population growth rate. The other exception was the process error. This had been given an informative prior[1] intended to have a mode at 4%, narwhal having low birth and death rates.

In general, there was not much data, and what there was had large uncertainties. Therefore it was not surprising that parameter estimates were generally associated with large standard errors. OpenBUGS considered that the model is only estimating about 11–12 effective parameters.

STOCK DYNAMICS, INCLUDING 2011 SURVEYS

The re-analysis of the 2011 observations using the multi-strip methods used in 2000 halved the estimates of surface-visible numbers. The original line-transect estimates of numbers lay about 50% over the extension of the trend line estimated using the earlier surveys, while the estimates that were based on the re-analysis lay about 30% below it (Table 2; Figure 1a). When the line-transect estimates were included in the calculation of population trend, the

[1] Runs with uninformative priors for the process error tended to hang, having too much freedom and not enough direction.

estimate of annual population growth increased by nearly a percentage point; when the multi-strip re-analysis was used instead, it decreased. There were concomitant differences in the estimates of numbers in 2011.

Table 2. Median estimates of survey and stock-dynamic parameters resulting from three treatments of the 2011 survey data. IQR (interquartile range) values are shown in parentheses. Relative IQR = IQR divided by the median.

	Option 1 2011 surveys not included in trend analysis[1]	Option 2 2011 survey original analysis equals early surveys	Option 3 2011 survey revised analysis equals early surveys
Annual population growth (%)	1.9 (2.4)	2.8 (2.0)	1.2 (1.9)
Early survey visibility (%) (IQR)	32 (3.3)	31 (3.3)	32 (3.3)
Visibility ratio 2011 line-transect analysis: early surveys (%) (Relative IQR (%))	149 (70)	100 (0)	198 (41)
Visibility ratio 2011 re-analysis: early surveys (%) (Relative IQR (%))	71 (70)	51 (43)	100 (0)
Visual survey CV (%)	33	32	32
Photo survey CV (%)	20	20	20
Mean Deviance[2]	51.6	51.5	51.5
DIC	63.2	62.9	62.8
Process error correlation (%)	25	67	50

[1] The population trajectory was projected forward from 2000; 2011 surveys were included in the data but allowed to have free correction factors. Wager Bay sightings in 2011 therefore increased the stock size estimates from earlier surveys.

[2] The Deviance Information Criterion (DIC) tool, built into the OpenBugs platform, measures how well the model fits the data.

The Wager Bay surveys, included as separate surveys, had little effect on population trajectory. However, for all analysis options the numbers in Wager Bay were included in the population from which the catch is taken. The inclusion of these numbers therefore reduced the growth rate needed to sustain the catch. The Wager Bay counts also affected the model estimates of the relationship between the original line-transect analysis of the 2011 data and its re-analysis, and therefore also the estimates of the relative visibilities of the 2011 surveys and the earlier ones.

Most parameter estimates had large uncertainty (Table 2) as all results were based on the analysis of uncertain surveys that agreed poorly with each other and with the estimated population trajectory. Adding to the uncertainty was the poorly-known loss rate. The exception was the visibility in the early surveys, assumed the same for all, which was based on a set of satellite-tag readings of time near the surface which overall agreed with each other reasonably well. This visibility was estimated at 31% with an Interquartile range (IQR) of 3.3 percentage points.

The treatment of the 2011 surveys had a great effect on the conclusions. The original line-transect results lay well above the extrapolation of the median trend line based on the early surveys (Figure 1b), and assuming them comparable with the early surveys resulted in a large estimate both of numbers in 2011 and of the population growth rate, so future harvests even as high as 250 a year were reckoned to be sustainable (Table 3). The much lower re-analysed results had the opposite effect, leading to low estimates both of 2011 numbers and of growth rate (Figure 1c), so sustainable harvests needed to be as low as 50 a year (Table 3).

Table 3. Probability of decrease below 2011 numbers, estimated using two treatments of 2011 survey observations, for annual landed catch of 50–250 narwhals.

Landed catch (per year)	Probability (%) of decrease after a specified period, with 2011 observations analysed as:					
	line-transect survey			multi-strip survey		
	1 year	5 years	10 years	1 year	5 years	10 years
50	35	22	17	49	46	45
75	36	25	20	52	53	53
100	37	28	23	55	59	61
125	39	31	27	57	65	68
150	40	35	31	60	69	73
175	42	37	35	62	74	78
200	43	41	39	64	78	82
225	45	44	43	66	81	85
250	47	47	47	68	84	88

DISCUSSION

In order to fit the population trend line to all the survey results, including the 2011 results, the model not only altered the estimate of growth rate, it also adjusted the proportion of narwhals in Wager Bay, not surveyed in the early years. A lower proportion there decreased the estimates of total numbers corresponding to the early survey observations and made it easier to fit the low estimates from the 2011 multi-strip analysis; conversely, a higher proportion there gave higher early estimates of total numbers that are easier to fit with the high estimates from line-transect analysis.

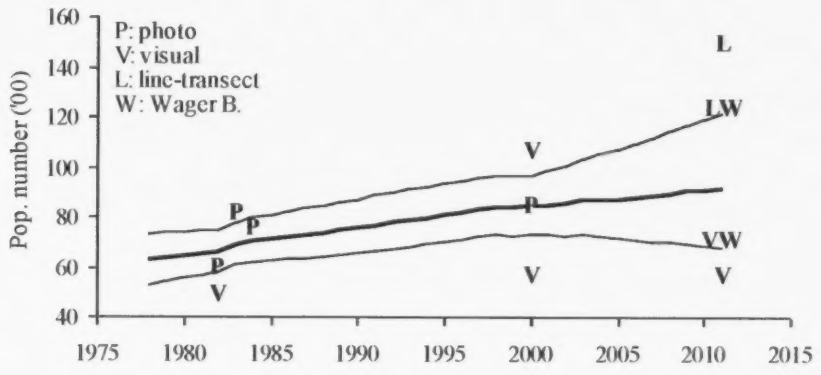

Figure 1a. Modelled trend of population number (with quartiles) based on surveys up to 2000 (option 1).

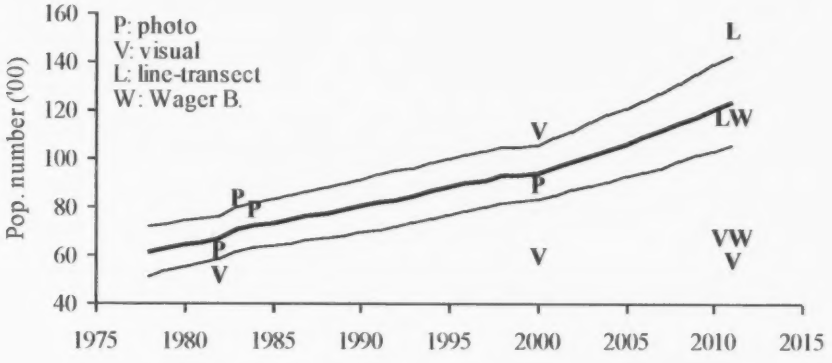

Figure 1b. Modelled trend of population number (with quartiles) including the 2011 line-transect analysis having visibility equal to earlier surveys (option 2).

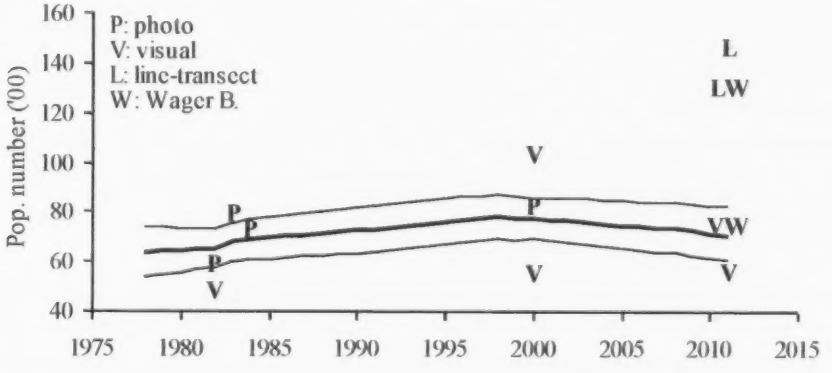

Figure 1c. Modelled trend of population number (with quartiles) including the 2011 re-analysis as multi-strip survey having visibility equal to earlier surveys (option 3).

The model also imposed serially correlated sequences of process errors (Figure 2) to aid the fitting of a constant growth rate to the sequence of survey results. Although the model

assumed the consecutive process errors to be independent, such correlated sequences are an inevitable consequence of incorporating process error in this type of model, and the correlation coefficients compare, at least qualitatively, how well the different assumptions fit the data.

The serial correlation was higher for the line-transect analysis of the 2011 observations (Figure 2a) than re-analyses of the 2011 observations as a multi-strip survey (Figure 2b), indicating that the results obtained from the latter analysis fitted better with the earlier surveys, the catch sequence, and the assumption of a constant population growth rate. Completely omitting the 2011 surveys from the trend analysis (option 1) produced a serial correlation of 25%; i.e., a part of the correlation is due to fitting to the surveys of the 1980s.

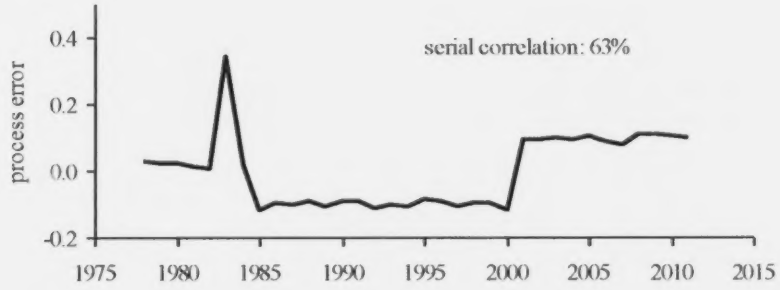

Figure 2a. Process errors imposed to fit a stock-dynamic model to survey results for northern Hudson Bay narwhals, assuming that line-transect surveys in 2011 had visibility equivalent to that of earlier surveys.

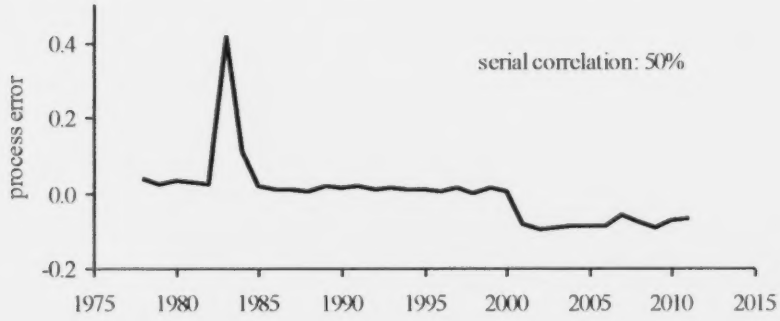

Figure 2b. Process errors imposed to fit a stock-dynamic model to survey results for northern Hudson Bay narwhals, assuming that observations in 2011 re-analysed as multi-strip survey had visibility equivalent to that of earlier surveys.

The view taken of the 2011 surveys had a great effect on the assessment of the stock, altering the estimate of allowable catch by a factor of about five. The statistical analysis of the results did not show decisively which (i.e., the line-transect results or the multi-strip re-analysis), if either, could or should be considered equivalent to the early surveys. There were several features of the methods used in 2011 that would be expected to lead to higher estimates than those of the multi-strip visual surveys of 2000 or the strip-transect survey flown in 1982. It was, however, not so obvious that they would induce similar increases over photographic surveys.

As far as we could tell, the use of two observers on each side of the plane and the photographic record for verifying doubtful sightings were each accountable for only small improvements. The principal cause of the large difference—a factor of about 2—between the line-transect results and the multi-strip re-analysis was due to applying the observations to an effective strip width of about 520 m instead of blocking more flexibly (e.g., about 250 m).

Assuming the re-analysis was equivalent to the early surveys supposed that the observers in 2011, using clinometers, would have had the same distance distribution of sightings as the observers in 2000, who were using window marks to bin sightings. There might, in fact, have been differences in the way they positioned their heads and observed. There was also an observation in the survey re-analysis document (Asselin and Ferguson 2012) that in 'Distance' sampling 'missing animals further out is not a problem'. If this philosophy had been applied differently in 2011, when distances were being individually measured, than in 2000, when the survey was essentially a multi-strip survey, then the distance distribution of observations might well have been different. The immediate result of the re-analysis of the 2011 data was that the number of observations in the first 200 m from the transect line was distinctly less than that in the second 200 m. However, this was not at all the same as the distribution recorded by Bourassa in 2000, when there were *more* observations in the first 200 m than the second. This discrepancy in the sighting-distance histogram gave some indication that the distribution of distances was different in 2011 from what it was in 2000, perhaps owing to differences in observation and recording methods.

Maintaining an assumption that the re-analysis of the 2011 line-transect observations using the methods of 2000 should give results equivalent to those of the earlier surveys led, independently of conclusions about population status or growth rate or sustainable harvest or the assumptions about the validity of estimating visibility by satellite-tag near-surface time, to the conclusion that the line-transect survey as originally designed and executed had a visibility roughly double that of the early surveys, including photographic surveys. It is a standard assumption that photographic-survey visibility is well estimated by the near-surface time estimated from satellite tagging studies, although this has not been confirmed by direct studies of the visibility of narwhals in the field under survey conditions.

It is probable that the type of line-transect survey executed in 2011, which based its density estimate on observation near the platform, would produce higher estimates than the multi-strip surveys carried out in 2000. That said, it seems also possible that the re-analysis overestimated the difference.

CONCLUSION

Assuming that the re-analysis of the 2011 data gave results that were comparable with earlier visual surveys, the population has a growth rate of 1.2% a year and can support landed catches no higher than 75 a year. However, some results of the re-analysis and of the stock-dynamic modelling cast doubt on the validity of this assumption. Resolution of the current uncertainty in population trend is unlikely until new line-transect surveys are flown using methods and coverage comparable to the 2011 survey. These results suggest that the approach to determining sustainable harvest levels should continue to use Potential Biological Removal (PBR), rather than the risk-based approach reported in this document, until more surveys are undertaken.

REFERENCES

Asselin, N.C., and Ferguson, S.H. 2013. A re-analysis of northern Hudson Bay narwhal surveys conducted in 1982, 2000 and 2011. DFO Can. Sci. Advis. Sec. Res. Doc. 2013/019. iv + 10 p.

Asselin, N.C., Ferguson, S.H., Richard, P.R. and Barber, D.G. 2012. Results of narwhal (*Monodon monoceros*) aerial surveys in northern Hudson Bay, August 2011. DFO Can. Sci. Advis. Sec. Res. Doc. 2012/037. iii + 23 p.

Bourassa, M.-N. 2003. Inventaires de la population de narvals (*Monodon monoceros*) du nord de la Baie d'Hudson et analyse des changements démographiques depuis 1983. Thesis (M.Sc.) University of Quebec at Rimouski, Rimouski, Quebec. 69 p.

Kingsley, M.C.S., Richard, P. and Ferguson, S.H. 2012. Stock-dynamic model for the northern Hudson Bay narwhal population based on 1982-2008 aerial surveys. DFO Can. Sci.Advis. Sec. Res. Doc. 2012/020. iv + 20 p.

Richard, P.R. 1991. Abundance and distribution of narwhals (*Monodon monoceros*) in northern Hudson Bay. Canadian Journal of Fisheries and Aquatic Sciences 48: 276-283.

Richard, P.R. 2008. On determining the total allowable catch for Nunavut odontocete stocks. DFO Can. Sci. Advis. Sec. Res. Doc. 2008/022 iv + 12 p.

Richard, P.R. 2010. Survey index of the northern Hudson Bay narwhals, August 2008. Can. Sci. Advis. Sec. Res. Doc. 2010/021. iv + 17 p.

Thomas, L., Buckland, S.T., Rexstad, E.A., Laake, J.L., Strindberg, S., Hedley, S.L., Bishop, J.R.B., Marques, T.A., and Burnham, K.P. 2010. Distance software: design and analysis of distance sampling surveys for estimating population size. Journal of Applied Ecology 47(1): 5-14. doi:DOI 10.1111/j.1365-2664.2009.01737.x

Westdal, K.H. 2008. Movement and diving of northern Hudson Bay narwhals (*Monodon monoceros*): relevance to stock assessment and hunt co-management. Thesis (M.Sc.) University of Manitoba, Winnipeg, MB. 103 p.

APPENDIX 1.
MATHEMATICAL DESCRIPTION OF THE MODEL

1. Visibility of narwhals to photographic survey.

Behaviour data were available from tagging studies cited by Westdal (2008) and used to update a prior distribution for the presumed visibility of narwhals to photographic surveys:

$$O_i = v_2 + \varepsilon 3_i$$

where O_i is the proportion of time that the i^{th} narwhal on its summering grounds in northern Hudson Bay was estimated to be within 2 m of the surface and so visible to vertical aerial photography. The visibility v_2 was given a wide prior uniform in log space; the error terms $\varepsilon 3$ were Normally distributed with zero mean, and a prior distribution for their precision was set as Gamma(0.01, 0.01). For analyses in which visual and photographic surveys were assumed to have different visibilities, the visibility to visual survey was given a wide prior uniform in log space.

2. Loss correction of landed catches

The true catch T_y in year y was related to the reported (landed) catch R_y by a loss factor L (lost : landed), assumed the same in all years:

$$T_y = R_y \cdot (1 + L)$$

The factor L was given a log-normal distribution with parameters (-1.55, 1.45) giving a modal value close to 0.1 and a mean of 0.3.

3. Adjusting estimates for coverage varying from survey to survey

The expected true population N_S in the area covered by survey S was given by:

$$N_S = \sum_A p_A \cdot C_{A,S} \cdot P_{Y_S}$$

P_{Y_S} being the true population in year Y_S and $C_{A,S}$ a binary variable indicating whether stratum A, which held a proportion p_A of the population, was covered by survey S, which was flown in year Y_S.

The proportions p_A were given a Dirichlet prior with values 29, 22, 16, 3 and 30 % and assumed to be based on 6 observations. (The 'number of observations' defines how informative a Dirichlet prior is.)

4. Adjusting estimates by applying visibility corrections

The survey result V_S was then estimated by:

$$V_S = (N_S \cdot v_{K_S} \cdot r_s) \cdot \varepsilon 2_S$$

where v_{Ks} was the visibility[2] of narwhals to surveys of type *K*, either photographic or visual, r_s was an *ad hoc* survey correction factor and the $\varepsilon 2_S$ were log-normal (0, $\sigma 2^2$). The precisions of the distributions of the $\varepsilon 2_S$ (reciprocal of $\sigma 2^2$) was given a prior distribution gamma(0.1, 0.1). Visual and photographic surveys had different values of $\sigma 2^2$. Survey correction factors were given priors uniform in log space.

5. Progressing population numbers

True population numbers were progressed from year to year by the relationship:

$$P_{y+1} = \left(\left(P_y - 0.25T_y\right)\cdot\left(1+r\right) - 0.75T_{y+1}\right)\cdot \varepsilon 1_y$$

Surveys are flown in mid- to late summer. This relationship implies that three-quarters of the year's catch is taken before survey flying and a quarter after, and that all births and non-hunt mortality take place between the end of one hunting season and the start of the next. The process-error term $\varepsilon 1$ has a log-normal distribution with a highly informative prior (gamma(2,0.0048)) designed to give a modal value of 0.04.

APPENDIX 2. DATA NEAR-SURFACE TIME

The following values represent mean proportion of time within 2 m of the surface for nine narwhals satellite-tagged in northern Hudson Bay as reported by Westdal (2008).

0.349, 0.286, 0.314, 0.4, 0.27, 0.382, 0.305, 0.261, 0.279

[2] The ratio of animals counted on a survey to animals in the surveyed area (i.e., a single correction factor to be applied to counts).

APPENDIX 3.
DATA ON LANDED CATCHES

Landed harvests from the northern Hudson Bay narwhal population by community (0=no harvest, blank cell=no report) (from Appendix 4 in Stewart unpubl. report (2008) and DFO unpubl. data as of 3 May 2012). The model used the catch series presented in the "Total" column.

Year[1]	Cape Dorset	Chesterfield Inlet	Coral Harbour	Kimmirut	Rankin Inlet	Repulse Bay[2]	Whale Cove	Total[3]
1977	0		0	0	0		0	**0**
1978	2		0	0	0	4	0	**6**
1979	1		0	0	0	30	0	**31**
1980	1		0	0	0	25	0	**26**
1981	0		0	0	5	29	0	**34**
1982	0		0	0	0	21	1	**22**
1983	0		0		0	11	0	**11**
1984			0	0	2	25	0	**27**
1985	0		0	0	1	15	0	**16**
1986	0		0	0	0	7	0	**7**
1987	0		12	7	0	16	0	**35**
1988	1	0	0	0	0	25	0	**26**
1989	0	0	0	0	0	16	0	**16**
1990	0	0	0	0	0	17	0	**17**
1991	16	0	0	0	0	3	0	**19**
1992	0	0	0	0	0	20	0	**20**
1993	0	0	1	0	0	13	0	**14**
1994	1	0	0	0	0	5	0	**6**
1995	0	0	10	0	6	4	0	**20**
1996	0	0		0	0	16	0	**16**
1997	0	0		0	0	35		**35**
1998	0	4		0		18	0	**22**
1999	0		0	0		154	0	**154**
2000	0	3	0	0		42	0	**45**
2001	1	2	0	0	5	99		**107**
2002	0	4	4	1	2	56	0	**67**
2003	0	1	1	0	3	38		**43**
2004	0	4	3	0	7	106	0	**120**
2005	0	4	6	0	3	72	1	**86**
2006	0	4	3	0	10	75	2	**94**
2007	0	3	1	1	9	74	0	**88**
2008	0	2	1	0	1	25	0	**29**
2009	0	4	8	0	8	97	2	**119**
2010	2	2	6	1	9	82	1	**106**[4]
2011	0	5	7	0	8	70	1	**91**[5]

[1] Starting year of the harvest reporting period. Prior to 1996, the harvest was reported by calendar year. Starting in 1996, the harvest has been reported by fiscal year (April 1 – March 31).

[2] As a participant in the Community Based Management program, Repulse Bay had flexible quota privileges that permitted carry-over of a portion of unused Marine Mammal Tags (MMTs) to the following year.

[3] In some years the community of Hall Beach may have taken narwhals in Lyon Inlet from the Northern Hudson Bay population. 2010 is the only year for which MMT returns indicate that two narwhals were harvested in Lyon Inlet. Landed catches by Hall Beach were not included in the model.

[4] The total includes three narwhals harvested by Arviat. Three MMTs were allocated to Arviat by the other Kivalliq communities in a 2010 Kivalliq Wildlife Board decision (one year only).

[5] The total includes one narwhal harvested by Arviat. As Arviat does not have a regulatory quota, the MMT was borrowed from Whale Cove.

APPENDIX 4. *BUGS* CODE FOR STOCK-DYNAMIC MODELLING OF NORTHERN HUDSON BAY NARWHALS

```
#line-transect survey analysis has same vis. as early surveys.
#all early surveys have the same visibility.

#data
list(area.pct=c(29,22,16,3,30), area.obs=6,
Nareas=5, Nsurv=12,
Nyears=35,
N.fut.years=10, Nlevel=9,
set.catch=c(0.50, 0.75, 1.0, 1.25, 1.50, 1.75, 2.00, 2.25, 2.50),
N.vis.obs = 9,
vis.obs=c(0.349, 0.286, 0.314, 0.4, 0.27, 0.382, 0.305, 0.261, 0.279),
#vis.obs = c(0.32) ,
#vis.obs = c(0.6, 0.4, 0.46, 0.38 ),
fut.surv.cover = c(1,1,0,0,0) )

# areas are 1. R.B & F.S. (always surveyed together); 2. Gore B. and Lyon In.; 3. N.W. Foxe Chann.; 4. N.E. Roes Welcome Sound; 5. Main Roe's Welcome Sound and Wager Bay (so far, only in 2011).

model {

lgt.true.pop.1 ~ dunif(0,2)
lgt.true.pop.1.prior ~ dunif(0,2)
true.pop[1] <- pow(10, lgt.true.pop.1)
true.pop.1.prior <- pow(10, lgt.true.pop.1.prior)
std.vis.pop[1] <- true.pop[1] * vis[2] * inprod(area.prop[], fut.surv.cover[])

true.catch[1] <- report.catch[1] * (1 + struck.and.lost)

for (i in 1:N.vis.obs)

{       vis.obs[i] ~ dnorm(vis[2],prec.vis)I(1.0E-1,)   # vis[2] is visibility to photo survey
}

for (yr in 2:Nyears)
{       true.pop.pred[yr] <- (true.pop[yr-1] - 0.25 * true.catch[yr-1]) * (1 + r) - 0.75 * true.catch[yr]
        true.pop.med[yr] <- log(max(1.E-3,true.pop.pred[yr]))
        true.pop[yr] ~ dlnorm(true.pop.med[yr],prec.proc)
        std.vis.pop[yr] <- true.pop[yr] * vis[2] * inprod(area.prop[], fut.surv.cover[])
        true.pop.offset[yr] <- (log(true.pop[yr]) - true.pop.med[yr] ) * sqrt(prec.proc)
        true.catch[yr] <- report.catch[yr] * (1 + struck.and.lost)
        decrease[yr] <- step(std.vis.pop[yr-1] - std.vis.pop[yr])
        for (area in 1:Nareas)
        {       area.true.pop[yr,area] <- true.pop[yr] * area.prop[area]
        }
}

for (surv in 1:Nsurv)  # visual surveys have code 1, photo. have code 2
{       surv.vis.pop[surv] ~ dlnorm(surv.vis.pop.med[surv], prec.type.surv[type[surv]])
        surv.vis.pop.pred[surv] <- inprod(area.true.pop[surv.year[surv],], surv.cover[surv,]) * vis[type[surv]] *
correction[surv]
        surv.vis.pop.med[surv] <- log(surv.vis.pop.pred[surv])
        prec.surv[surv] <- prec.type.surv[type[surv]]
        std.surv[surv] <- surv.vis.pop[surv]/inprod(area.prop[], surv.cover[surv,]) *
inprod(area.prop[],fut.surv.cover[])
        std.foto.surv[surv] <- std.surv[surv]*vis[2]/vis[type[surv]]
```

```
        std.totpop.surv[surv] <- surv.vis.pop[surv] / inprod(area.prop[],  surv.cover[surv,])  / vis[type[surv]]
}

#log.correction[1]  ~ dunif(-2,2)
correction[1]  <-  1 #  exp(log.correction[1])
correction[2] <- 1
correction[3] <- 1
correction[4] <- 1
correction[5] <- 1
correction[6] <- 1
correction[7] <- 1
log.correction[8] ~ dunif(-2,2)
correction[8]  <- exp(log.correction[8])  # survey 8 is the bad survey of 2008
#  surveys 9 and 10 are the high-number surveys in 2011.
correction[9]  <-  1
correction[10] <- correction[9]
log.correction[11] ~ dunif(-2,2)
correction[11]  <- exp(log.correction[11])  #11 and 12 are the re-analysis of 2011 data
correction[12] <- correction[11]

log.corr.8.prior ~ dunif(-2,2)
corr.8.prior  <-  exp(log.corr.8.prior)

base.vis.pop <- true.pop[Nyears] *  inprod(area.prop[],fut.surv.cover[]) * vis[2]

for (level in 1:Nlevel)
{       true.fut.catch[level] <- set.catch[level] * (1 + struck.and.lost)
        for (yr in 1:1)
        {       true.fut.pop.pred[level,yr] <- (true.pop[Nyears] - 0.25 * true.catch[Nyears]) * (1 + r) - 0.75 *
true.fut.catch[level]
                true.fut.pop.med[level,yr] <- log(max(1.E-3,true.fut.pop.pred[level,yr]))
                true.fut.pop[level,yr] ~ dlnorm(true.fut.pop.med[level,yr],prec.proc)
                fut.vis.pop[level,yr] <- true.fut.pop[level,yr] * inprod(area.prop[],fut.surv.cover[]) * vis[2]
                fut.decrease[level,yr] <- step(std.vis.pop[Nyears] - fut.vis.pop[level,yr])
                fut.decrease.90[level,yr]  <-  step(0.90 * std.vis.pop[Nyears] - fut.vis.pop[level,yr])
        }
        for (yr in 2:N.fut.years)
        {       true.fut.pop.pred[level,yr] <- (true.fut.pop[level,yr-1] - 0.25 * true.fut.catch[level]) * (1 + r) - 0.75 *
true.fut.catch[level]
                true.fut.pop.med[level,yr] <- log(max(1.E-3,true.fut.pop.pred[level,yr]))
                true.fut.pop[level,yr] ~ dlnorm(true.fut.pop.med[level,yr],prec.proc)
                fut.vis.pop[level,yr] <- true.fut.pop[level,yr] * inprod(area.prop[],fut.surv.cover[]) * vis[2]
                fut.decrease[level,yr] <- step(std.vis.pop[Nyears] - fut.vis.pop[level,yr])
                fut.decrease.90[level,yr]  <-  step(0.90 * std.vis.pop[Nyears] - fut.vis.pop[level,yr])
        }
}

#proportions in areas

for (area in 1:Nareas)
{       area.prop.base[area] <- area.pct[area]/sum(area.pct[]) * area.obs #area.obs is a dummy to set the
accuracy with which the area proportions are known.
        area.prop.gamma[area] ~ dgamma(area.prop.base[area],1)
        area.prop[area] <- area.prop.gamma[area]/sum(area.prop.gamma[])  #
}

#priors

r ~ dunif(-0.10,0.100)

r.prior ~ dunif(-0.0,0.100)
```

```
shape <- 2

rate <- .0016 * (shape + 1) # mode for process c.v. at 4%
prec.proc.prior ~ dgamma(shape , rate)
prec.proc ~ dgamma(shape , rate)

prec.vis ~ dgamma(0.01, 0.01)I(1.0E-8,)

log.vis.2 ~ dunif(-4,1)  #  type 2 surveys are photographic
vis[2] <-  exp(log.vis.2)
vis[1] <-   vis[2]
vis.diff <- vis[1]/vis[2]

for (i in 1:2)
{           prec.type.surv[i] ~ dgamma(.01,.01)I(1.E-8,)
}
struck.and.lost ~ dlnorm(-1.55,1.45)  # PRR recommendation 11/06/10
struck.and.lost.prior ~ dlnorm(-1.55,1.45)

prec.surv.prior ~ dgamma(.01,.01)I(1.0E-8,)

#bookkeeping

w[1]<-r
w[2]<-true.pop[1]

w[3]<-1/sqrt(prec.proc)

w[4]<-struck.and.lost
w[5] <- 1/sqrt(prec.vis)
w[6] <- vis.diff

w[8] <- base.vis.pop
w[11]<-vis[1]
w[12]<-vis[2]  #vis[2] is photographic

w[14] <- correction[8]
w[15] <- correction[9]  # 2011 original analysis cf. visual survey
w[16] <- correction[9] * vis.diff  # 2011 original analysis cf. photo survey
w[17] <- correction[11]  # 2011 re-analysis cf. visual survey
w[18] <- correction[11] * vis.diff  # 2011 re-analysis cf. photo survey

w[21]<-1/sqrt(prec.surv[1])
w[22]<-1/sqrt(prec.surv[2])

w[29]  <-  correction[1]  #  visual strip survey of 1982 cf. visual surveys 2000.

w1[1]<-r.prior
w1[2] <- true.pop.1.prior
w1[3]<-1/sqrt(prec.proc.prior)
w1[4]<-struck.and.lost.prior
w1[5] <- corr.8.prior
#w1[6] <- vis.diff.prior

for (i in 1:Nareas)
{           y[i] <- area.prop[i]
}

for (i in 1:Nsurv)
```

```
{       y1[100+i] <- std.surv[i] # standardised for coverage only
        y1[200+i] <- std.foto.surv[i]  # standardised for coverage and visibility
        y1[300+i] <- std.totpop.surv[i]  # standardised to total numbers, all areas
}

for (i in 1:Nsurv)
{       y2[100+i] <- std.surv[i] / correction[i]    # standardised for coverage only
        y2[200+i] <- std.foto.surv[i] / correction[i]    # standardised for coverage and visibility
        y2[300+i] <- std.totpop.surv[i] / correction[i]  # standardised to total numbers, all areas
}

for (i in 2:Nyears)
{       x[100+i] <- true.pop[i]
        x[200+i] <- std.vis.pop[i]
        x[300+i] <- true.pop.offset[i]
        x[400+i] <- decrease[i]
}

for (level in 1:Nlevel)
{       for (yr in 1:N.fut.years)
        {       z[level,100+yr] <- true.fut.pop.pred[level,yr]
                z[level,200+yr] <- fut.vis.pop[level,yr] # future std photo survey
                z[level,400+yr] <- fut.decrease[level,yr]
                z[level,500+yr] <- fut.decrease.90[level,yr]
        }
}

#end of model
}}}
```